Average transverse energy density for pions, kaons, φ mesons and Ω hyperons in the most central A+A collisions at RHIC and LHC

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Abstract

We are studying, for several types of particles (π, K, φ, Ω) with different numbers of strange quarks, the dependencies of the average transverse energy at midrapidity in the central $0-5\%$ Au+Au and Pb+Pb collisions over a wide range of $\sqrt{s_{NN}}$ from RHIC to LHC. We observe that the dependence for each particle type is described by a power-law function, and the exponent is universal for all studied particles—from light pions to multi-strange Ω-hyperons. This universal behavior leads to the fact that the ratios of the average transverse energy densities are practically independent of the collision energy, thus indicating on a possible single mechanism for their formation. We consider this statement within the framework of the multipomeron exchange model.

Introduction

In the study of high-energy heavy nuclei collisions, the enhanced production of particles containing strange quarks is widely considered [1] as a key signature for the formation of a new phase of matter, the quark-gluon plasma (QGP). It is assumed that hadrons with single or multiple strange quarks are particularly sensitive to the dynamics of this deconfined medium. With the formation of the QGP, a significant increase in the yields of $\varphi(1020)$ mesons , which contain a hidden strange-antistrange quark pair ($s\bar{s}$), was predicted [2].

Previously, we found [3] that the ratios of the fractions of Bjorken energy density for φ mesons to those of other identified hadrons (pions, kaons, and protons) were independent of the collision energy over a broad range. Naturally, these ratios of Bjorken energy densities are equivalent to the relevant ratios of transverse energy densities.

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The motivation for the present study is to build upon these findings and systematically expand our analysis to particles with different masses and stramgeness contenet.

The paper is organized as follows. First, we will outline briefly the procedure for estimating the average transverse momentum $\langle p_\perp \rangle$ basing on the available published HepData, and the subsequent calculation of the transverse energy density for each particle species. We will then present our results on the collision energy dependence of $\langle dE_\perp/dy \rangle$ for pions, kaons, φ mesons, and Ω hyperons, followed by the analysis of their ratios. In the final section, we discuss the potential implications of our findings for the determination of the efficient string tension within the frameworks of the generalized Multipomeron Exchange Model.

Methodology

The average transverse energy density, $\langle dE_\perp/dy \rangle$, is calculated for each identified particle species in the central rapidity region for the most central (0-5%) A+A collisions. The calculation follows the formula:

$$\frac{d\langle E_\perp \rangle}{dy} = \langle m_\perp \rangle \frac{dN}{dy} \tag{1}$$

Here, $\frac{dN}{dy}$ represents the mean particle yields at mid-rapidity, which are taken from published experimental data [4], [5], [6], [7], [8], [9], [10]. The mean transverse mass, $\langle m_\perp \rangle$, is derived from the mean transverse momentum, $\langle p_\perp \rangle$, using the relation $\langle m_\perp \rangle = \sqrt{m^2 + \langle p_\perp \rangle^2}$.

The values for $\langle p_\perp \rangle$ were obtained by integrating fits to the available experimental transverse momentum spectra [11], [12], [13]. To perform the fits and evaluate systematic uncertainties, two distinct functional forms were utilized: the Lévy distribution [14] and the Blast-Wave model [15].

1 Results of estimates of $\langle dE_t/dy \rangle$ for φ mesons and other particles

We have calculated the average transverse energy density, $\langle dE_\perp/dy \rangle$, for pions, kaons, φ mesons, and Ω hyperons. The data were analyzed for the most central (0-5%) Au+Au and Pb+Pb collisions at center-of-mass energies of $\sqrt{s_{NN}} = 39$ GeV, 200 GeV, and 2.76 TeV. A summary of the the particle multiplicity yields (dN/dy) at midrapidity and of our calculated values for $\langle p_\perp \rangle$, $\langle m_\perp \rangle$, and $\langle dE_\perp/dy \rangle$ is presented in Table 1. Please, note, that we show here in this work the results for the relevant half-sums of the transverse energies of particles under consideration (except φ-mesons).

The dependence of the average transverse energy density at mid-rapidity on the collision energy for all studied particles is shown in Figure 1. We observe that for each particle species, the data are well-described by a power-law function of the form $\langle dE_\perp/dy \rangle = Q \cdot (\sqrt{s_{NN}})^n$. The fitted values of the power-law exponent, n, for each particle are summarized in the caption to the figure. A notable finding is that the exponents for all particle species are similar in values in the range from RHIC to LHC, thus suggesting a common scaling behavior with the collision energy.

The primary result of this study is presented in Figure 2, which shows the ratios of the average transverse energy density of the φ meson to that of pions, kaons, and Ω hyperons as a function of $\sqrt{s_{NN}}$. The key observation is that these ratios are practically flat across the entire range from RHIC to LHC energies. This remarkable constancy suggests that the relative production dynamics of these particles, despite their different masses and strangeness content, remain surprisingly stable as the collision energy increases.

2 THE MULTIPOMERON EXCHANGE MODEL

Previously, it was shown in the framework of the generalized multipomeron exchange model for multiparticle production in hadron-hadron collisions [16], that the quark-gluon string fusion concept [17] could be very successful in the description of yields of strange, multi-strange and charm particles as a function of multiplicity in pp, p-Pb and Pb-Pb collisions at the LHC energy, observed in [18]. Each cut pomeron exchange corresponds to a pair of quark-gluon strings. In case of high density, with growing energy and size of the colliding system, these quark-gluon strings start to overlap, forming clusters. The last ones are characterized by the higher tension or stronger color fields, thus capable for creation of particles with a higher transverse momentum and for the increased yield of particles containing strange quarks [17],[19]. Strings decay through formation of quark-antiquark color neutral pairs and subsequently hadronize to produce the observed hadrons[17], [19].

It is the Schwinger mechanism [20] of particle creation that is responsible here for the increased yield of strangeness in high-multiplicity events of $A + A$ collisions due to the formation of strong color fields (in clustes of fused quark-gluon strings) at the initial stages of hadronic collisions. This mechanism describes satisfactorily the “soft” region of the spectrum of observed particles in a wide range of data produced in the high-energy hadronic collisions. In case of high densities of strings formed in central $A + A$ collisions, new particle-emitting sources – clusters of strings, could appear due to the processes of color string fusion. They are characterized by higher string tension (and higher energy density). In this case the yields of the particles with a higher transverse momentum and of particles containing strange or charm quarks are increased. In Schwinger mechanism of particle production, the transverse momentum distribution of charged particles from a string or cluster with tension denoted as k has a Gaussian form:

$$\frac{dN}{dy} \sim |\mu| \sim \exp\left(-\frac{\pi\langle m_\perp\rangle^2}{k}\right) \tag{2}$$

The mean transverse mass $\langle m_\perp\rangle$ of the particle is defined as in eq. (2). Quark-gluon strings and clusters formed due to the fusion of strings will differ in string tension k due to the higher energy density in case of formation of a cluster of fused strings. It is the observation of the constant ratios of transverse energies of φ mesons and other particles, measured at midrapidity at different energies of collisions, that motivate us to assume that both φ mesons and other particles are produced by the same particle production source.

We used the generalized multipomeron exchange approach [16] to calculate the string tension coefficient k basing on the constant ratios of transverse energies of φ mesons and other particles. We define the ratio of transverse energies of φ mesons and π, K -mesons and Ω-hyperons in the framework of [16] as:

$$\frac{\langle \frac{dE_\perp}{dy} \rangle_\varphi}{\langle \frac{dE_\perp}{dy} \rangle_{particle}} = \frac{\frac{dN_\varphi}{dy}}{\frac{dN_{particle}}{dy}} \frac{(2S_\varphi + 1)\langle m_\perp \rangle_\varphi \exp\left(-\frac{\pi \langle m_\perp \rangle_\varphi^2}{k}\right)}{(2S_{particle} + 1)\langle m_\perp \rangle_{particle} \exp\left(-\frac{\pi \langle m_\perp \rangle_{particle}^2}{k}\right)} = R_{exp} \tag{3}$$

Here S_φ and $S_{particle}$ are spins of φ mesons and other mesons. The right-hand value R_{exp} of eq.(3) is defined at given value of $\sqrt{s_{NN}}$ according to Table I as $R_{exp}(\sqrt{s_{NN}})$ the mean experimental ratio obtained at definite collision energy. Therefore, after some transformation in eq. (2) one can get the mean value of this string tension coefficient k:

$$k = \frac{\pi(\langle m_\perp \rangle_{particle}^2 - \langle m_\perp \rangle_\varphi^2)}{\ln\left(\frac{R_{exp} \cdot (2S_{particle}+1) \cdot \langle m_\perp \rangle_{particle}}{(2S_\varphi+1) \cdot \langle m_\perp \rangle_\varphi}\right)} \tag{4}$$

The observation of constant ratios of transverse energies for different particle species motivates the assumption that they are produced from the sources with similar characteristics. This allows us to use the model to extract the effective string tension, k. We define from the experimental ratio of eq.(4) this effective string tension parameter k, and we denote it below as t_{eff} .

It should be noted that the complete formula of eq.(3) also should include the matrix elements characterizing particle decays. These elements were omitted in the ratios of our previous analysis, as their contribution is less significant for the heavy hyperons like the Ω. In this work also, we will not consider in our analysis these terms for consistency, but we plan to introduce it in the future calculations involving other particles.

We utilize our observation of constant transverse energy ratios to calculate the effective string tension coefficient, t_{eff}, using the relationship eq.(4) for k as it was mentione above. The calculated values of t_{eff} using the transverse energy ratios of φ mesons to pions, kaons, and Ω hyperons are presented in Table 2. As can be seen from the Table 2, the values obtained from the φ/π and φ/K ratios are consistent with each other, yielding an effective tension of $t_{eff} \approx 1.0 - 1.4$ GeV^2. In contrast, the tension derived from the φ/Ω ratio is significantly higher, resulting in $t_{eff} \approx 2.0 - 3.0$ GeV^2. This higher value is notably close to the value of $t_{eff} = 1.9\ GeV^2$ obtained independently for central Pb+Pb collisions at the LHC within the same multipomeron exchange model [16]. The values of efficient string tension values are substantially higher than that of a single quark-gluon string, lending further support to the string fusion hypothesis as a key mechanism in central nucleus-nucleus collisions.

3 CONCLUSION

We have performed a systematic analysis of the mean transverse energy, $\langle dE_\perp/dy \rangle$, for π-mesons, K-mesons, φ-mesons, and Ω-hyperons at midrapidity in the most central 0-5% $Au+Au$ and $Pb+Pb$ collisions over a wide energy range from $\sqrt{s_{NN}} = 39$ GeV to 2.76 TeV.

The primary result of this study is that the ratios of the mean transverse energy of the φ-mesons to that of the π-meson, K-mesons, and Ω-hyperons, while different in value, are all found to be practically constant across the entire collision energy range investigated.

The Multipomeron Exchange Model with collective effects of string fusion was used to analyze this observed energy independence. Within this framework, we have calculated the effective string tension coefficient, t_{eff}, from these ratios. The analysis indicates some increase of t_{eff} with increasing collision energy. Notably, the value of t_{eff} derived from the ratio involving the Ω-hyperon is significantly larger than those derived from ratios with pions and kaons, suggesting that multi-strange particles may originate from sources with a higher degree of string fusion.

As a part of our future work, we plan to extend this analysis to include protons and lambda-hyperons, particles with masses close to that of the φ-meson. We will also continue the analysis of these transverse energy ratios within the Multipomeron Exchange Model and compare the results with predictions from other theoretical models to further elucidate the underlying particle production mechanisms in heavy-ion collisions.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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$\sqrt{s_{NN}}$	Part	⟨dN/dy⟩	$\langle p_\perp \rangle$, GeV/c	⟨mt⟩, GeV	⟨dE/dy⟩, GeV	R_{exp}
39	π^+,π^-	185,7±20,5 182,27±20,1 [10]	0.417±0.025 0.413±0.025 [10]	0.438±0.001	80.5±0.05	0.052±0.001
	K^+, K^-	31,97±0,02 25,01±0,02 [10]	0.608±0.037 0.612±0.037 [10]	0.786±0.001	22.30±0.02	0.18±0.01
	φ	3.38±0.48[4]	0.69±0.08	1.73±0.09	4.16±0.9	—
	Ω+$\bar{\Omega}$	0.165±0.015 [4]	0.93±0.08	3.73±0.12	0.32±0.04	13.2±3.8
200	π^+,π^-	322±25 327±25 [8]	0.422±0.022 0.427±0.022 [8]	0.45±0.03	144.9±11	0.075±0.001
	K^+, K^-	51.3±6.5 49.5±6.2 [8]	0.720±0.074 0.719±0.074 [8]	0.87±0.06	44.02±8.5	0.25±0.06
	φ	7.7±0.3 [6]	0.97±0.02	1.406±0.09	10.84±0.3	—
	Ω+$\bar{\Omega}$	0.26±0.02 [5]	1.1±0.11	2.00±0.17	0.53±0.07	20.5±3.4
2760	π^+,π^-	733±54 732±52 [9]	0.517±0.019 0.520±0.018 [9]	0.539±0.031	393.2±39	0.058±0.010
	K^+, K^-	109±9 109±9 [9]	0.876±0.026 0.867±0.027 [9]	1.002±0.023	109.3±11.5	0.21±0.03
	φ	13.8±1.8 [7]	1.31±0.07 [8]	1.66±0.07	22.9±3.8	—
	Ω+$\bar{\Omega}$	0.595±0.095 [7]	1.8±0.1	2.46±0.06	1.46±0.25	15.6±5.2

Table 1: Summary data on values of mean energy densities at midrapidity ($|y| < 0.5$) in (0-5%) in Au+Au and Pb+Pb collisions as a function of $\sqrt{s_{NN}}$ for φ mesons and π, K -mesons and Ω hyperons. Data on $< p_\perp >$ are obtained in this work by fitting HEPdata spectra. Available data on dN/dy are also shown, as well as calculated values of $m_\perp$, ⟨dE/dy⟩ and ratios R_{exp} as defined in eq.(4) relevant to ⟨dE/dy⟩ for φ mesons and π, K -mesons and Ω hyperons. Quoted errors are the combined statistical and systematic uncertainties. Half sums of ⟨dE/dy⟩ are used in case of π, K -mesons and Ω hyperons.

Particles/ $\sqrt{S_{NN}}$	π	K	Ω
39 GeV	0.8 ± 0.5	0.87 ± 0.5	2.03 ± 1.07
200 GeV	1.08 ± 0.7	1.01 ± 0.6	1.73 ± 0.9
2760 GeV	1.4 ± 0.6	1.42 ± 0.6	3.0 ± 0.9

Table 2: Values of efficient string tension coefficients t_{eff} (in GeV^2) estimated in our work at three collisions energies obtained from eq.(4) for the ratio of mean transverse energies of φ mesons to π, K -mesons and Ω hyperons. In eq.(4), as well as in Table 1, the half sum of $\langle$dE/dy$\rangle$ were used in the analysis of t_{eff} in case π, K -mesons and Ω hyperons.

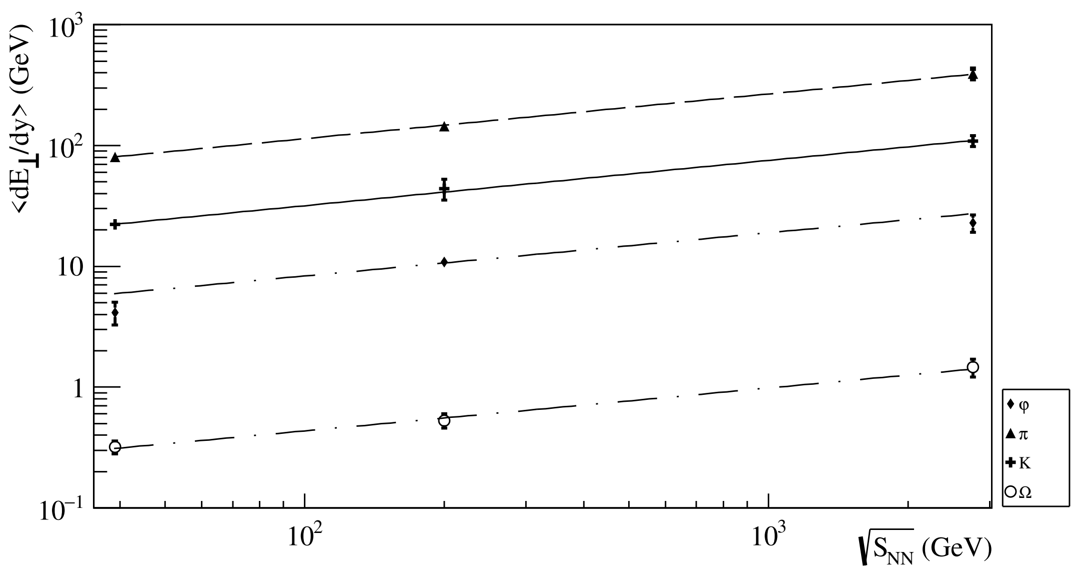

Figure 1: Values of mean energy densities at midrapidity ($|y| < 0.5$) obtained in our work using data in (0-5%) in $Au + Au$ and $Pb + Pb$ collisions as a function of $\sqrt{s_{NN}}$ for φ mesons and π, K -mesons and Ω hyperons. Lines are the results of power-law fits. We show only statistical uncertainties. The systematic ones are estimated to be below 10%. Fit parameters for π mesons: $\chi^2/NDf = 0.06/1, n = 0.37 \pm 0.02, Q = 20.8 \pm 1.6$. Fit parameters for K mesons: $\chi^2/NDf = 0.12/1, n = 0.37 \pm 0.02, Q = 5.6 \pm 0.5$. Fit parameters for φ mesons: $\chi^2/NDf = 5.6/1, n = 0.36 \pm 0.04, Q = 1.6 \pm 0.4$. Fit parameters for Ω hyperons: $\chi^2/NDf = 0.2/1, n = 0.36 \pm 0.05, Q = 0.08 \pm 0.02$.

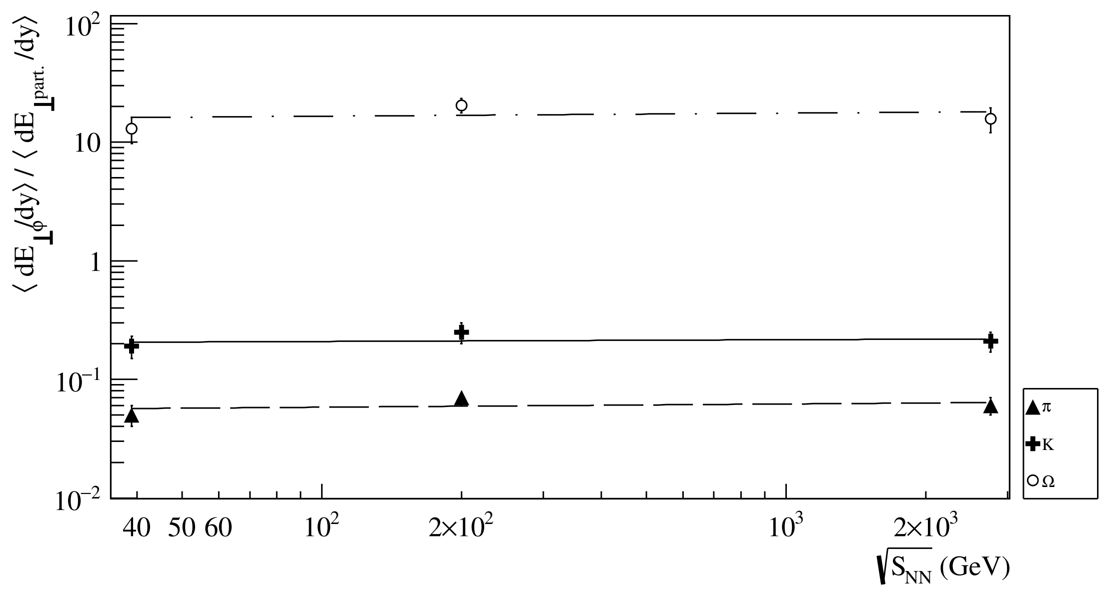

Figure 2: Ratio of energy densities at midrapidity ($|y| < 0.5$) in (0-5%) in Au+Au and Pb+Pb collisions as a function of $\sqrt{s_{NN}}$ for φ mesons and π, K -mesons and Ω-hyperons. Dash-dotted line is the results of power-law fits. Fit function: $Q \cdot (\sqrt{s})^n$. Fit parameters for π mesons: $\chi^2/NDf = 1.7/1, n = 0.03 \pm 0.05, Q = 0.05 \pm 0.02$. Fit parameters for K mesons: $\chi^2/NDf = 0.8/1, n = 0.01 \pm 0.06, Q = 0.19 \pm 0.07$. Fit parameters for Ω hyperons: $\chi^2/NDf = 2.98/1, n = 0.03 \pm 0.06, Q = 14.7 \pm 5.4$.